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EXTENDABLE RETRACTABLE TELESCOPIC MAST FOR DEPLOYABLE STRUCTURES

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The Extendable and Retractable Mast (ERM) which is presently developed by DORNIER in the frame of an ESA-contract, will be used to deploy and retract large foldable structures. The design is based on a telescopic carbon-fibre structure with high stiffness, strength and pointing accuracy. To verify the chosen design, a breadboard model of an ERM was built and tested under thermal vacuum (TV)-conditions. It is planned as a follow-on development to manufacture and test an Engineering Model Mast. The Engineering Model will be used to establish the basis for an ERM-family covering a wide range of requirements.

INTRODUCTION

The continuous trend to larger, heavier and retrievable spacecraft demands a new generation of strong and stiff masts in order to support large deployable structures. Such Extendable and Retractable Masts are already manufactured at DORNIER for use as radio link masts for ground application (Fig. 1). By developing and refining the deployment principle of these masts to take into account specific space requirements, a design satisfying a wide range of applications can be realized.

This design, which was carried out under cover of an ESA-contract, establishes the basis for a family of masts of use mainly in the carrying of large payloads.

At the present time two main space applications for an Extendable and Retractable Mast are proposed. They are the deployment of a Solar Array and the positioning of an Unfurlable Antenna.

The most important design-drivers were as follows:
- improvement of the state of the art in terms of strength and stiffness per unit deployed mass
- small total mass and stowed volume
- high interface adaptability
- need for tubes built from advanced composite materials
- high deployment length
- high number of possible deployment/retraction cycles
- good pointing accuracy

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TECHNICAL CONCEPT

The ERM is defined as a hybrid structural/mechanical device that can be stored in a minimum volume whilst yielding maximum deployed length, strength and stiffness.

The baseline for design and analysis of such an ERM was given by a set of requirements covering the applications of a) a Solar Array Mast with a deployment length of up to 40 m and b) an Antenna Mast of 20 m extended length as baseline. Investigations have shown that, within the required stowed length of 3 m for the 40 m ERM, a deployable length of up to 60 m can be reached without changing the stowed envelope length. Most of the required performance data (e.g. high stiffness and strength, good pointing accuracy, low thermal distortions, and low mass) can only be fulfilled by application of carbon-fibre technology in combination with a structurally optimized mast concept. Consequently a design was evolved which is based on the use of thin-walled telescopic tube-sections with circular cross-sections manufactured from Carbon Fibre Reinforced Plastics (CFRP). Comparison with hexagonal and triangular cross-sections and frameworks have shown that the circular design gives a good relation between stiffness and mass and, in addition, good thermostability and pointing accuracy. The good pointing accuracy expected at the ERM-tip is achieved by the use of an accurate and thermostable CFRP structure and by designing for minimum backlash in the tube joints. The design of the tube joints incorporates special guiding elements and these allow adjustment to very small backlash between the different tube sections. Furthermore the given mass budget requires a lightweight design of the electronics and electromechanical components and of the chosen thermal hardware. The ERM design optimization process has shown that the only significant difference between an ERM designed for use with a Solar Array and one designed for use with an Antenna is choice of thermal hardward defined according to mission requirements.

The ERM telescopic mast is driven by a spindle, powered by a brushless DC-motor which is coupled via a gear stage directly to the spindle. Each of the nested tube sections is provided with a threaded nut at its lower end. In the storage mode the nuts are retained by the unthreaded storage-section of the spindle with only the topmost nut engaging the thread. Deployment starts by virtue of the spindle pushing the engaged nut forward, rotational movement of the adjacent tube section being prevented by longitudinal stringers attached to the next outer tube. Shortly before the moving nut leaves the spindle an end-stop draws out the next outer tube of the storage-section and engages the corresponding nut to the spindle thread, whilst the nut of the preceding tube section leaves the spindle. At the same time a special latching system located on the upper end of each tube-section locks the extended tube to the next outer tube. This procedure can be repeated until the mast has reached its fully deployed position. During retraction the process is reversed. During deployment and retraction the ERM can be stopped at any arbitrary position

without losing key performance characteristics. Figure 2 shows the ERM tube-stack principle.

The maximum deployment length which can be reached by the mast is given mainly by the required envelope (length and diameter) and by the choice of the overlapping length; this corresponds to the thickness of the threaded nuts moving on the spindle. To optimize the tube-stack with respect to maximum stiffness and deployment length for minimum mass, a tube stack was chosen which has variable overlapping lengths, thus providing an almost constant ratio between tube diameter and overlapping length (Fig. 3). A payload interface is provided on top of the inner tube section and, if required by the application, on top of each outer tube section.

The dependency between deployment length and number of tube sections of the chosen ERM design is such that with a 3 m stowed envelope length a deployed length of up to 70 m can be reached whilst with a stack length of 2.25 m a deployment length of approximately 30 m can be achieved. However to reach an optimal design it is not adequate to go to very long deployed lengths at a given stowed envelope. This limitation for the optimal design is given by the chosen overlapping length which becomes longer for increasing tube diameters; consequently the deploying part of each tube section becomes shorter with the chosen number of tube sections. To minimize mass for a required deployment length the stowed envelope length should be chosen in a way that the dependency between deployment length and necessary number of tube sections is quasi-linear (Fig. 4). The curves according to Figure 4 reach a maximum and decrease again for increasing number of tube sections because of the decreasing extended length of each tube at certain value of the maximum overlapping length.

Table I gives an overview of ERM performance characteristics as achieved by the chosen design. This data has been categorized into Launch Characteristics (for the stowed and deploying mast) and Mission Characteristics (for the deployed mast).

TABLE I. - ERM PERFORMANCE CHARACTERISTICS

	40 m Solar Array Mast	20 m Antenna Mast
Launch Characteristics		
stowed envelope length	3 m	2,25 m
stowed envelope diameter	0.5 m	0.4 m
overall ERM-mass 1)	90 kg	50 kg
number of tube sections	18	13
1st natural frequency, stowed conf.	115 Hz	140 Hz
deployment speed,nominal	20 mm/s	10 mm/s
gear stage concept	spur gear 1 : 10	planetary gear up to 1 : 25
power consumption,nominal	80 W	
peak power consumption	200 W	
drive	brushless DC	
orbiter interface	basic flange and two hardpoints on top	
payload interface	hole pattern	
Mission Characteristics		
deployed length	40 m	20 m
payload capability 2)	40 kg on top plus 10 kg/m line load plus 100 N eccentric load	120 kg on top
max. bending moment	2800 Nm	2300 Nm
average bending stiffness	$7 \cdot 10^5$ Nm^2	$4 \cdot 10^5$ Nm^2
1st natural frequency, depl. conf. 3)	0.06 Hz	0.1 Hz
random translational deployment error	< 100 mm	< 30 mm
random angular deployment error	< 2 m rad	< 1.5 m rad
power lines to payload 4)	4 + 1 grounding	
signal lines to payload 4)	15	

1) without thermal hardware and cable follow-up mechanism

2) offset of eccentric force 0.5 m to CL / offset of Antenna Mast tip mass 6 m

3) 240 kg on tip and 70 kg distributed / 120 kg on Antenna Mast tip with 6 m offset and 40 kg distributed along Mast.

4) spring driven cable follow-up mechanism with slip rings is provided optionally for both Mast concepts

DESIGN DETAILS

Tube Structure

The tube structure is manufactured out of 6 layers of high-modulus carbon fibre epoxy resin in a symmetrical fibre lay-up. The resulting wall thickness of the CFRP tubes is only about 0.5 mm. The lay-up is optimized to reach high bending stiffness at a near zero thermal expansion coefficient.

A CFRP sandwich-plate carrying a Teflon-bronze thread is glued to the bottom of each tube section. At the upper end of the tubes a stiffening carbon fibre end-cone is mounted. On the inner surface of each tube segment three longitudinal stringers are mounted to prevent rotational movement of the next inner tube segment during extension and to provide torsional stiffness in the tube joints. To guide each tube relative to its neighbour it was necessary to develop special lightweight teflon-bronze guiding elements mounted to the upper and lower ends of the overlapping lengths. The space between two adjacent tubes was chosen as 10 mm, this being the minimum value required by the guiding elements and the inter-tube latching system. To avoid local loading of the thin-walled tube segments the guiding elements attached to the whole circumference of each moving tube are mated directly to the smooth inner surface of the next outer tube section. Because of the big influence of backlash on pointing accuracy it was necessary to shape the CFRP-tube sections and their guiding surfaces to very high accuracy (corresponding to a backlash of 0.1 mm). If, during integration or test, an ERM CFRP-tube should be damaged, it is possible to integrate a new tube-section without loss of performance by means of a procedure which involves simultaneous refurbishment of the teflon-bronze guiding elements. Figure 5 shows an ERM CFRP-tube with completely integrated guiding elements.

In order to minimize tip deflections, a mission dependant thermal design has been derived. Depending on the application, SSM-foil or white thermal point will be used while, to fulfill extreme pointing accuracy requirements, multilayer insulation can also be applied.

Mechanisms

The mechanisms necessary to operate the ERM are mainly those in the following assemblies:

- Latching mechanisms (latching of the adjacent tube sections)
- Drive mechanisms (gear stage with drive, launch locking device and spindle)
- Cable follow-up mechanism

Special problems were posed by the functional requirements of the ERM latching system:

- mutual latching of the stowed tube segments in the stowed configuration and achievement of a defined tube by tube extension during deployment
- sequential latching of adjacent tube sections as each reach their required extension.
- delatching of the retracting tube segments
- latching of the tube sections after retraction.

To assure these tasks a self-acting latching system was developed where all functions are satisfied by a single mechanical system. Each tube section has three latches mounted equidistantly around the circumference of its upper end. The latches are accessible for ground maintenance routines in the deployed configuration. Figure 6 shows a latching unit before integration with its tube-section.

The hollow Aluminium spindle used to deploy the tube-sections is coated with Ematal and reinforced by a CFRP-tube (Fig. 7) to reduce the axial coefficient of thermal expansion and, at the same time, to increase bending stiffness. As separate hardware options, the spindle can be driven either by a normal spur gear stage or by a planetary gear, this providing flexibility with respect to application dependant deployment speed, torque and power requirements. The brushless DC-drive is controlled by a fully redundant ERM Deployment Electronics Unit (DEU). Inductive position indicators provide signals to the DEU so that each required ERM position can be reached. To avoid inadvertent deployment of unsupported payloads due to vibration loads during launch, a magnetic clutch is incorporated to fix the gear stage in the required position.

Depending on the ERM emission, it may be necessary to provide power and signals to the payload. This task is performed by a cable follow-up mechanism which can be attached to the upper end of the outermost tube. A flat cable is guided along the extending tube sections in a manner rather like a fishing line on the rod. The mechanism is driven by a constant torque spring motor so that the cable is wound onto a drum during the retraction process.

Use of an external guidance system for the ERM cable gives advantages of accessibility not only during assembly (and disassembly) but also in the event of failure in orbit. To cover the latter eventuality, an astronaut-override is included in the design.

DEVELOPMENT STATUS

The detailed design phase started in 1984 and includes design, manufacturing and development testing activities. In addition, a complete set of manufacturing drawings will be produced for a qualification model ERM.

To verify functional performance of the ERM design a breadboard model, consisting of three tube sections, was built. This was tested in vacuum over the temperature range +85 to -100 deg C at ESTEC. The overall number of duty cycles (1 cycle = 1 extension + 1 retraction) was more than 600. The two extending CFRP-tube-sections had diameters of 405 and 425 mm respectively and each were of about 1.2 m length. The tubes were shaped according to the chosen ERM-design and equipped with design-representative guiding and latching systems. All friction interfaces, including the spindle-nut interface, were design representative. The outermost tube was manufactured in Aluminium. This acted as a dummy tube used to support the CFRP-tubes and to verify the latching function in the stowed configuration. The model was driven by a standard brushless AC-motor, modified for vacuum application. Figure 8 shows the ERM breadboard model during ambient functional testing.

During duty cycle testing in vacuum the spindle torque necessary to deploy and retract the system was measured as a function of deployed position, an eccentric resistive force of 100 N being applied at a distance of 0.5 m from the mast centerline. Figure 9 shows the dependency of peak torque on testing temperature.

The increase of torque at low temperatures is caused mainly by the difference in the coefficients of thermal expansion (CTE) between the Aluminium spindle and the Teflon-bronze nut. The slight increase of torque at high temperature is attributed to a reduction of backlash in the tube joints. During post test visual inspection, no serious degradation effects on the tube-structure or other structural parts could be found. Measurement of play between the teflon-bronze guiding elements and the adjacent CFRP-tube surface showed, however, that the medium backlash-value, as measured around the circumference of the tubes, had increased to around 0.29 mm from about 0.15 mm measured before testing. The degradation of the guiding elements was caused mainly by the axial eccentric force applied during TV-testing. The test set-up during thermal vacuum testing is shown in Figure 10.

CONCLUSION

By its use of CFRP technology, the ERM achieves an advantageous combination of high strength and stiffness and low mass. Because of the lack of hinges and fittings, which are necessary for example for deployable truss structures, good pointing accuracy can be reached with the ERM-design if the number of tube-sections is minimized. This minimization process results in a relatively long stowed envelope with a small outer diameter. For example deployed lengths of 6 m to 40 m result in stowed lengths of between 1.5 and 3.3 m.

For the next stage in the development of the ERM it is planned to build and test an Engineering Model (EM) with a deployed length of about 15 m consisting of 6 tube-sections. The EM will have a tube stack length of about 3 m and an outer diameter of 0.4 m. In the center of the tube stack 8 additional tube-sections could be mounted, leading to a maximum deployed length of about 32 m.

The EM will be subjected to a qualification test programme, consisting of the following:

- Functional performance
- Sinus vibration and acoustic noise
- Thermal vacuum duty cycle testing
- Static load test
- Alignment and pointing accuracy

In addition consideration is being given to the possibility of in-orbit testing for verification of pointing accuracy and dynamic behavior.

For the reasons given above, the ERM telescopic mast is a most promising system for achieving long deployed lengths with a high stiffness and a high pointing accuracy. Such applications are apparent in the large deployable structures envisaged in the Space Station and Columbus Programmes. Figure 11 shows such ERM application on the Columbus Resource Module, for the positioning of communication antennas and solar array panels.

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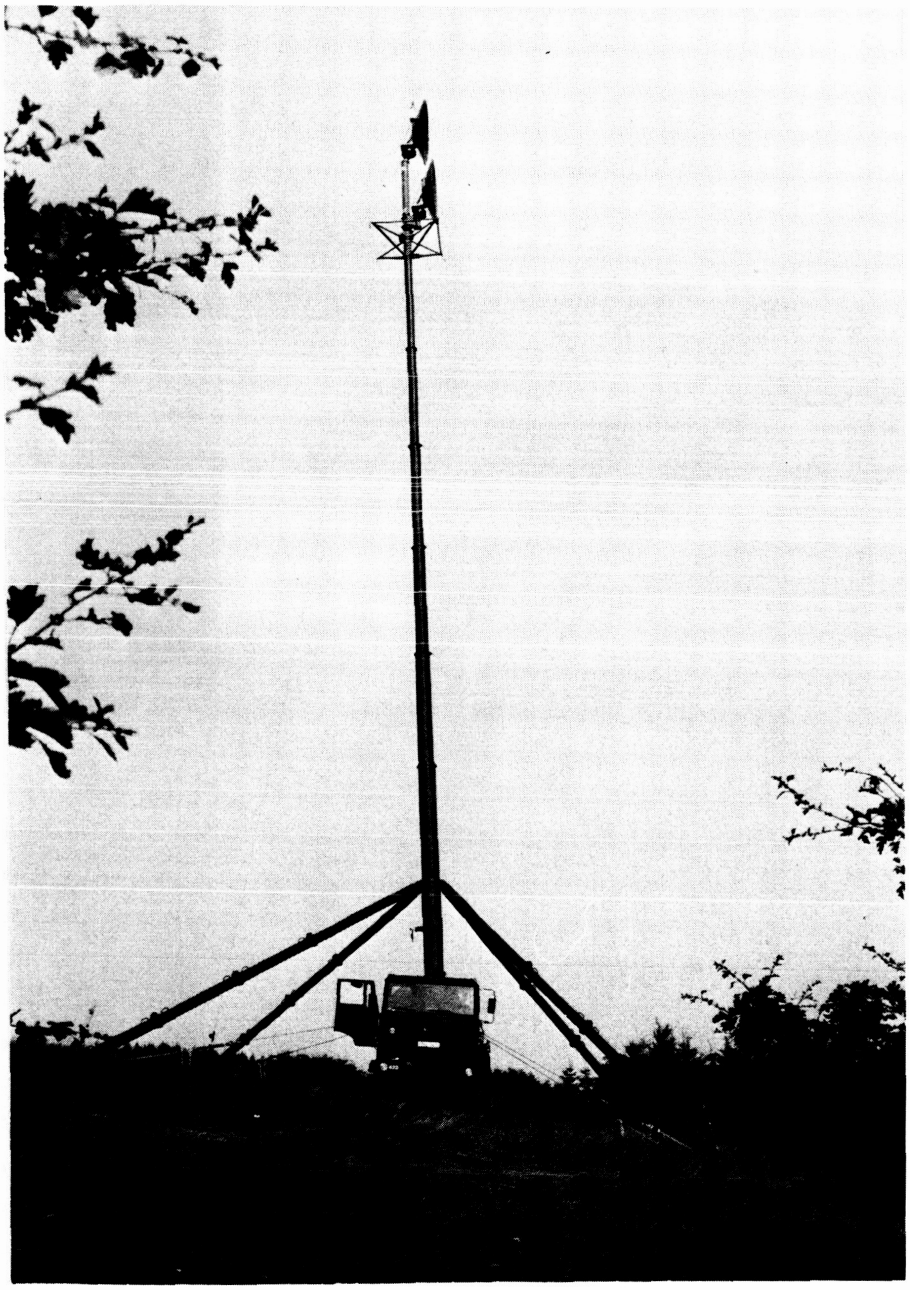

Figure 1. - DORNIER radio link mast for ground application.

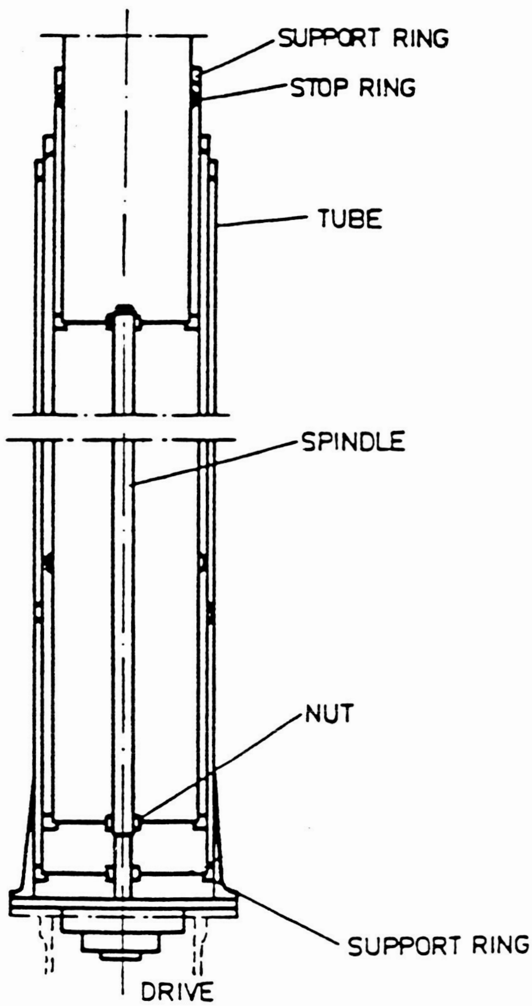

Figure 2. - ERM tube stack and working principle.

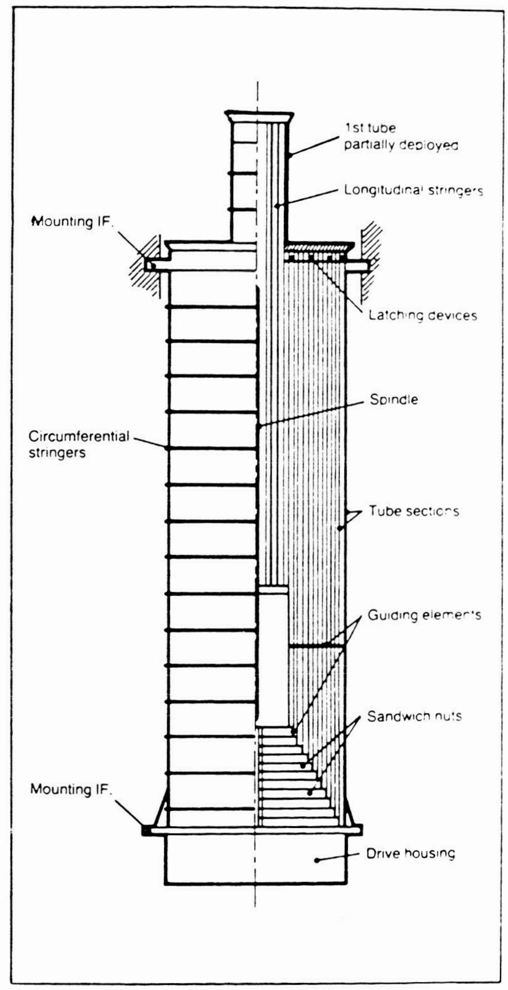

Figure 3. - Chosen ERM configuration with variable overlapping length.

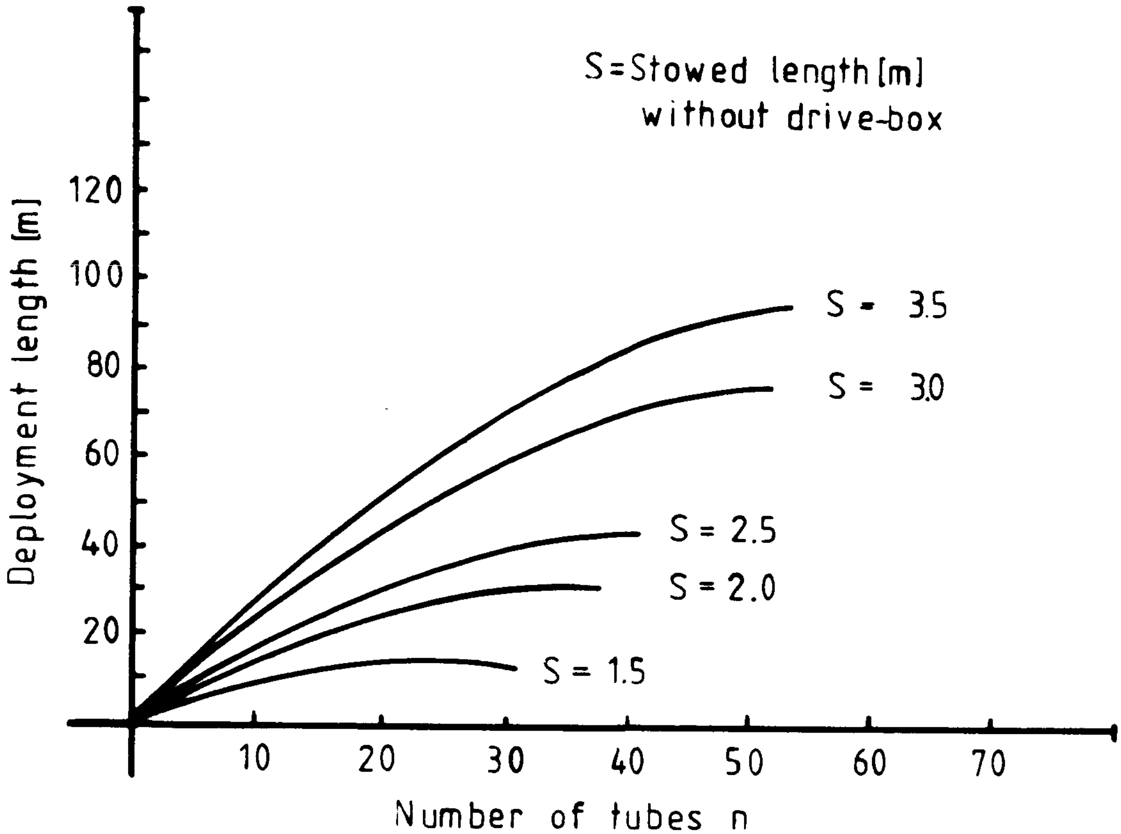

Figure 4. - Deployment length as function of number of tube-sections.

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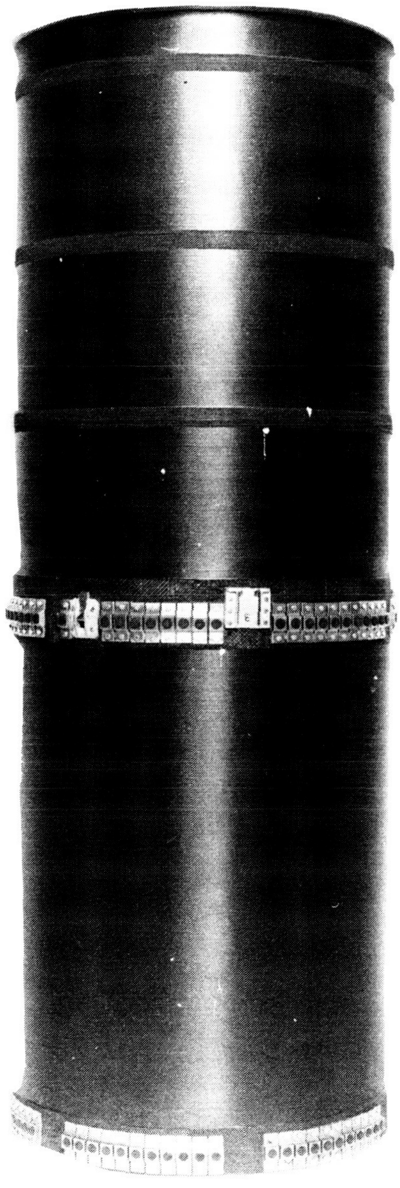

Figure 5. - ERM tube fully integrated with guiding elements.

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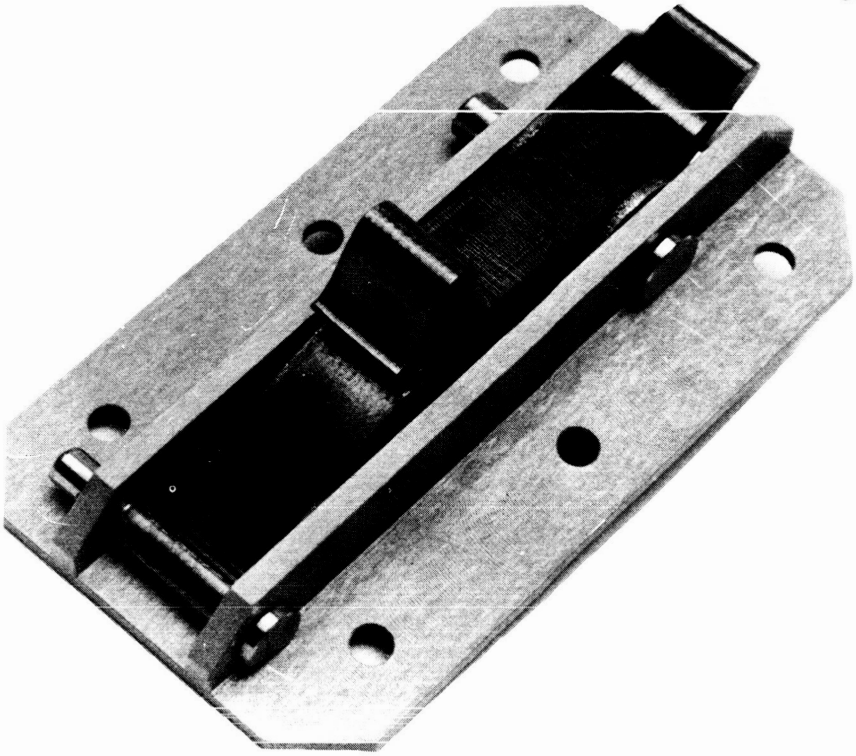

Figure 6. - Deployment latching unit.

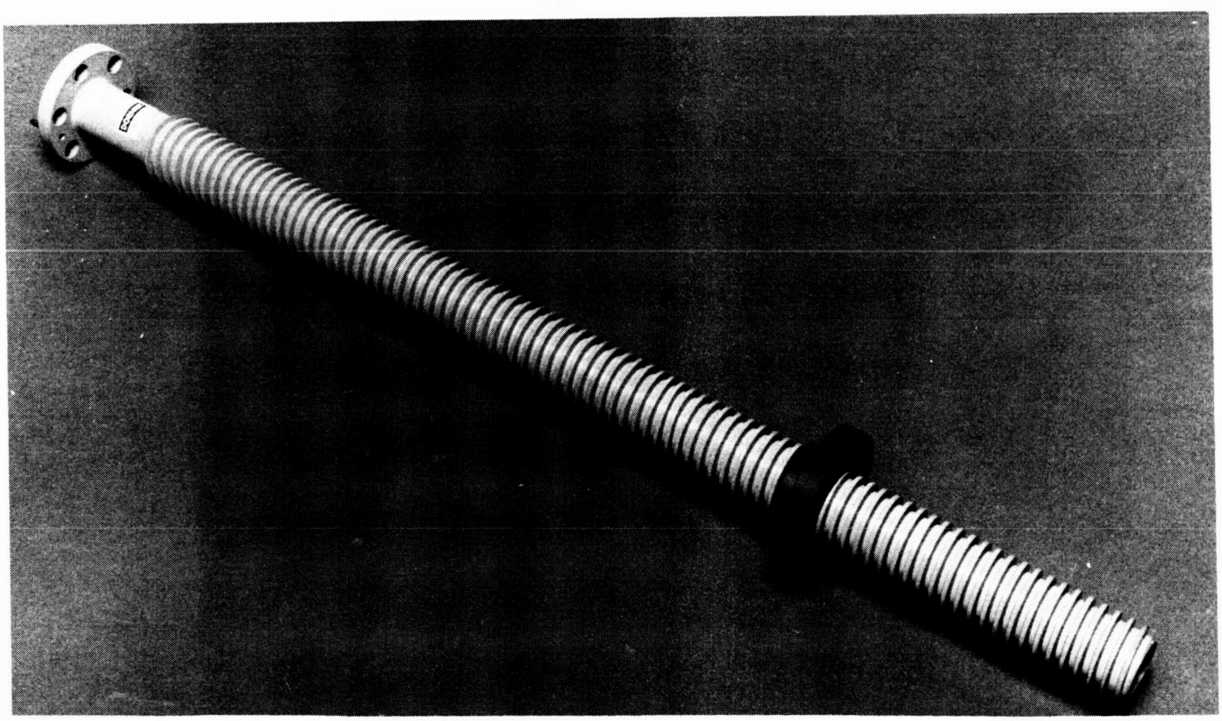

Figure 7. - Hollow aluminium spindle, ematal-coated.

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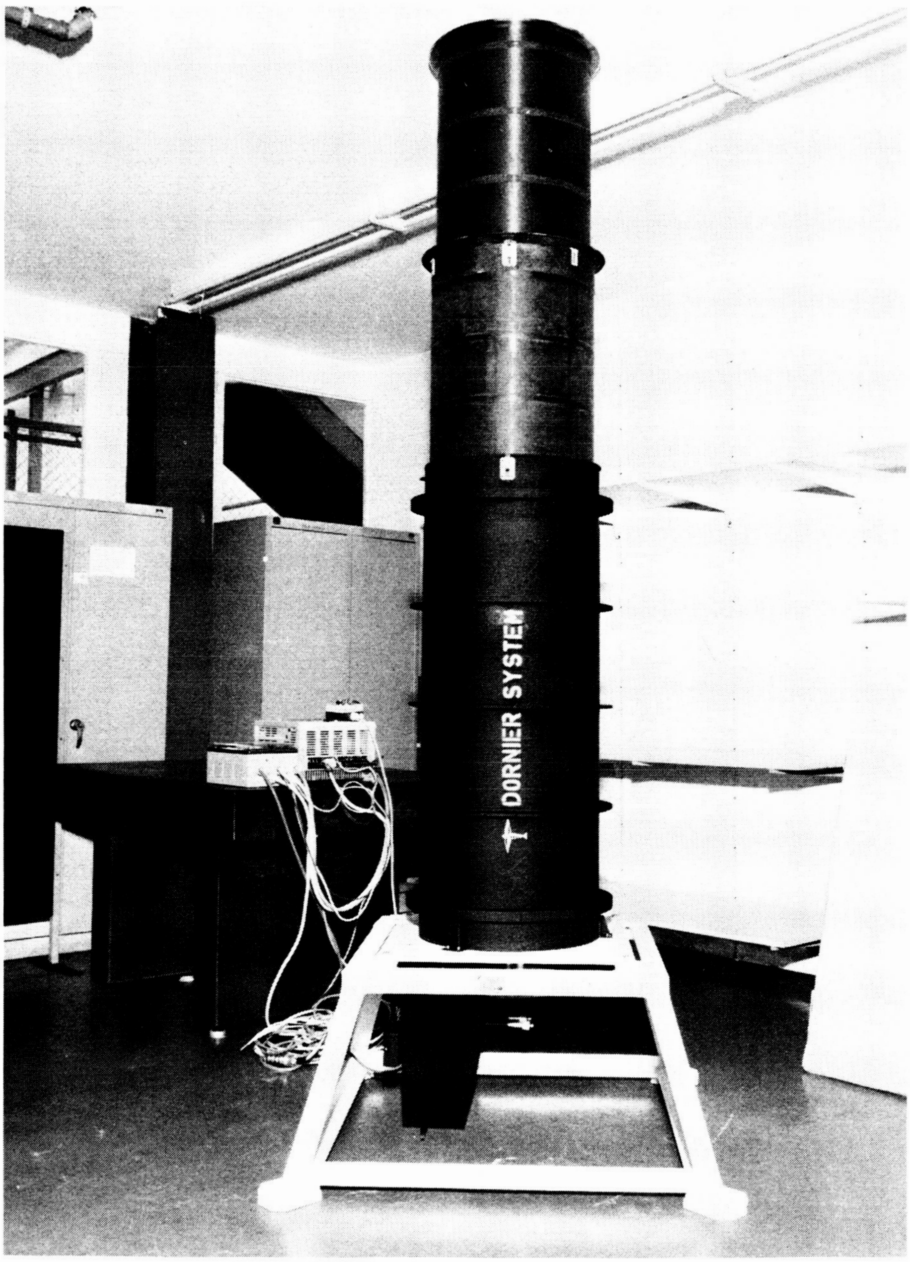

Figure 8. - Breadboard model during functional testing.

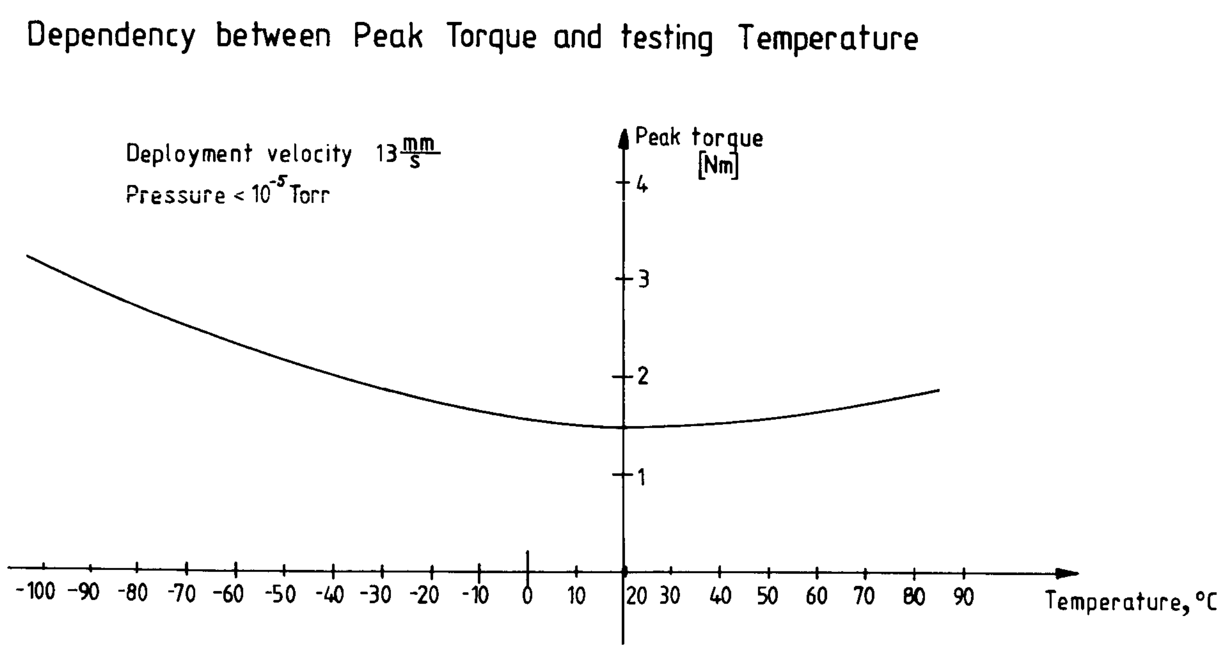

Figure 9. - Peak spindle torque required for different test temperatures.

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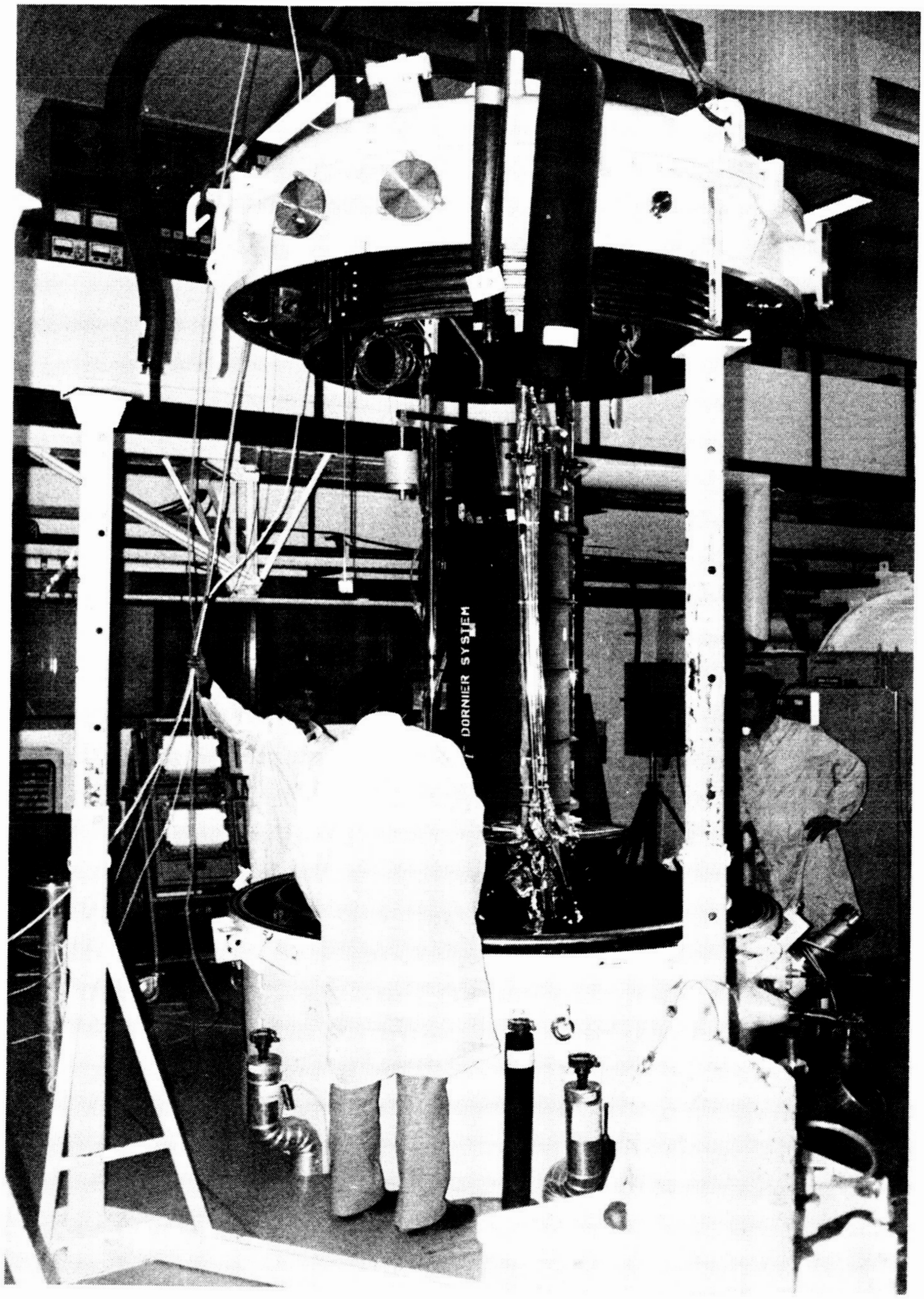

Figure 10. - Breadboard model during thermal vacuum (TV)-testing.

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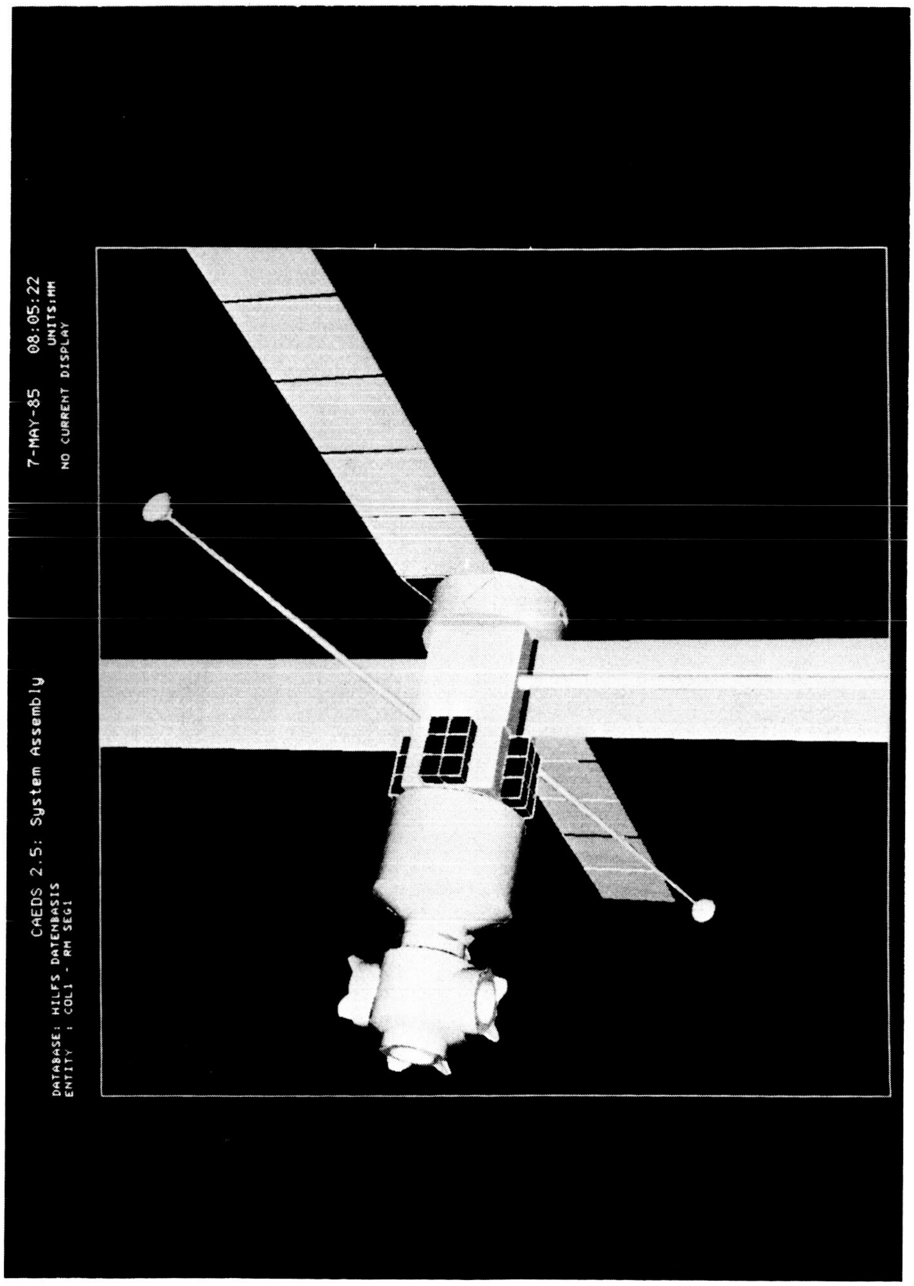

Figure 11. - Solar array and antenna masts on Columbus Resource Module.